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(54) **Bandpass filtering preamplifier**

(57) A balanced bandpass preamplifier assembly 23 is disclosed for use in a locator for locating a beacon transmitter housed within an underground boring device. The bandpass preamplifier assembly includes a balanced bandpass filter 28 of the Butterworth type with second order filter characteristic. The preamplifier assembly may provide reception of beacon frequencies at two distinct frequencies. The antenna of the locator forms the series inductance in the bandpass filter.
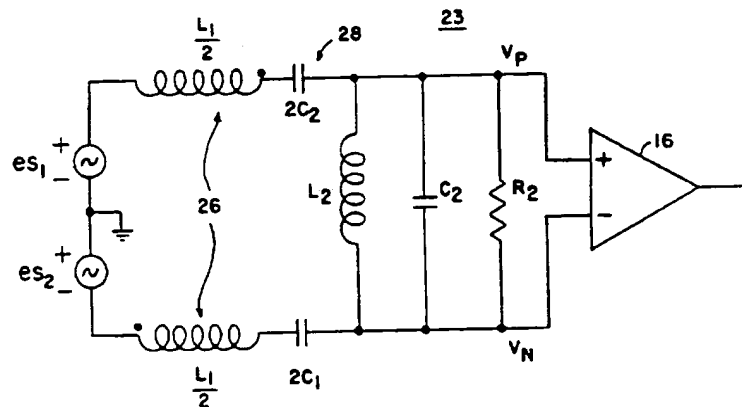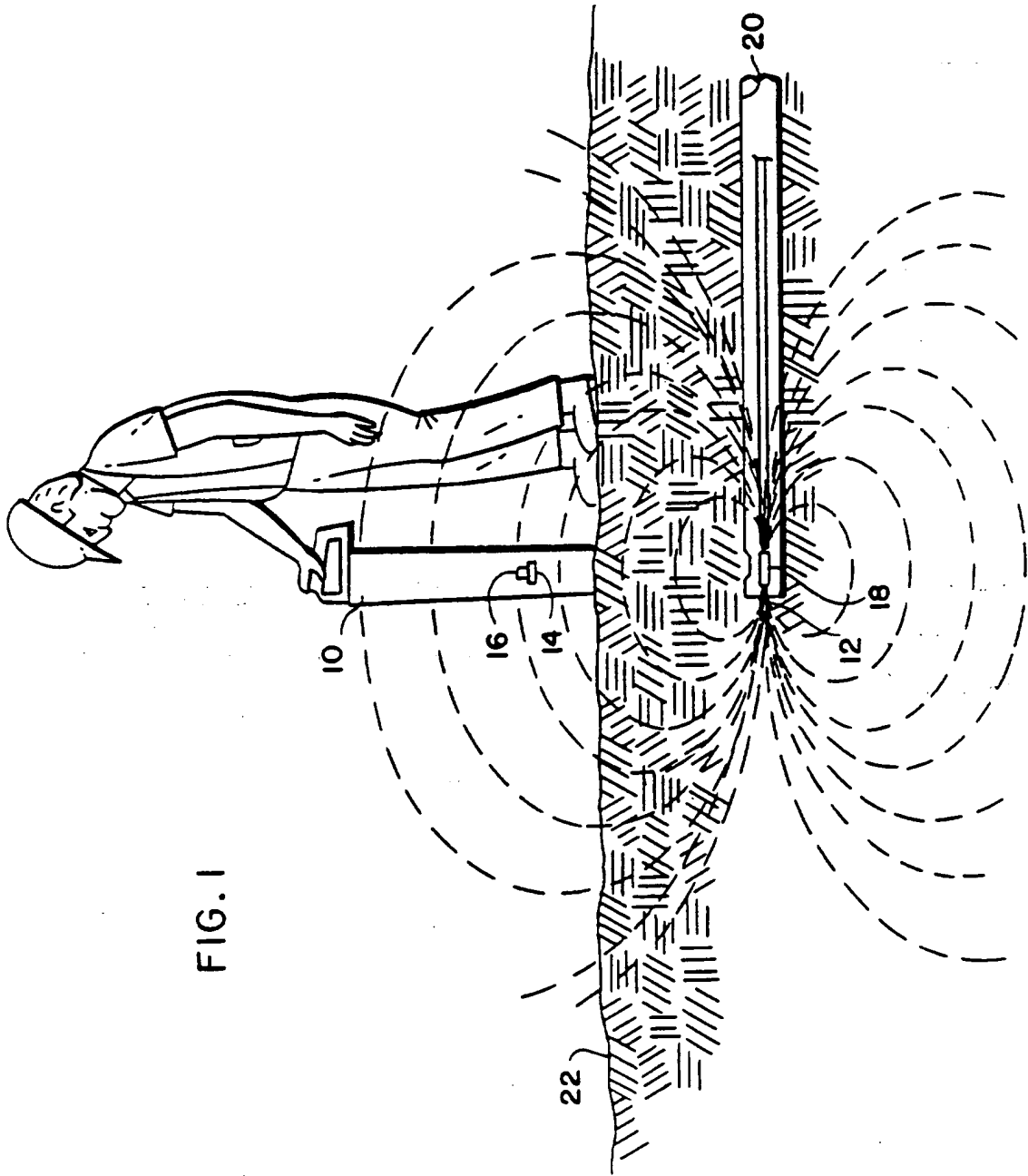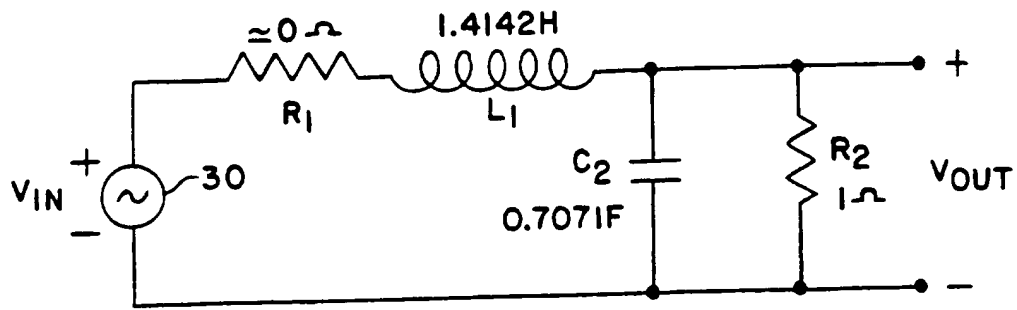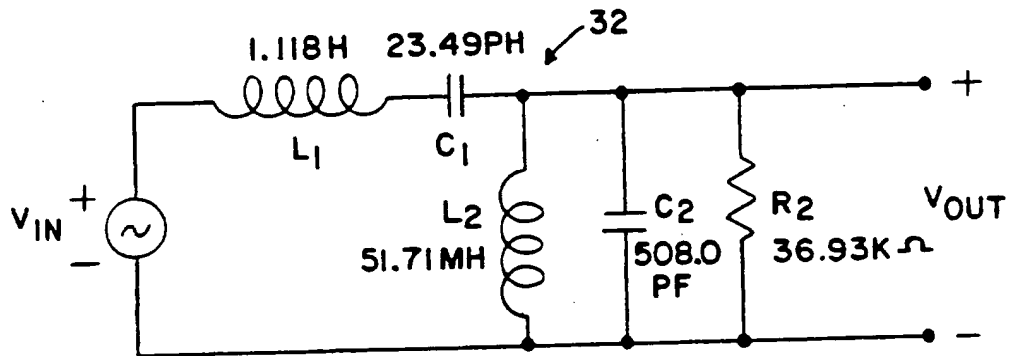
FIG.5
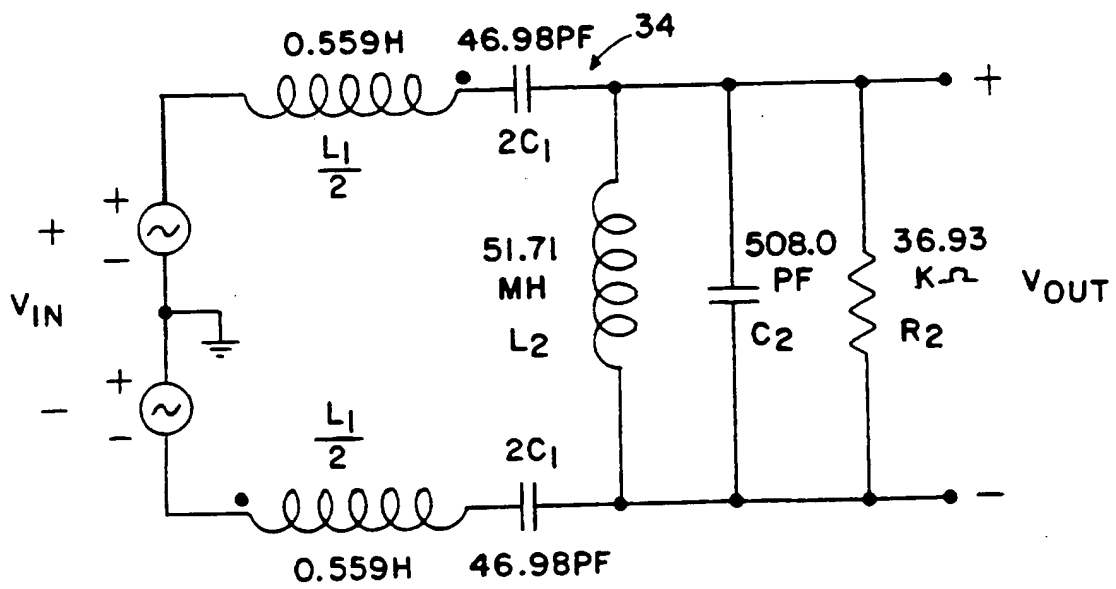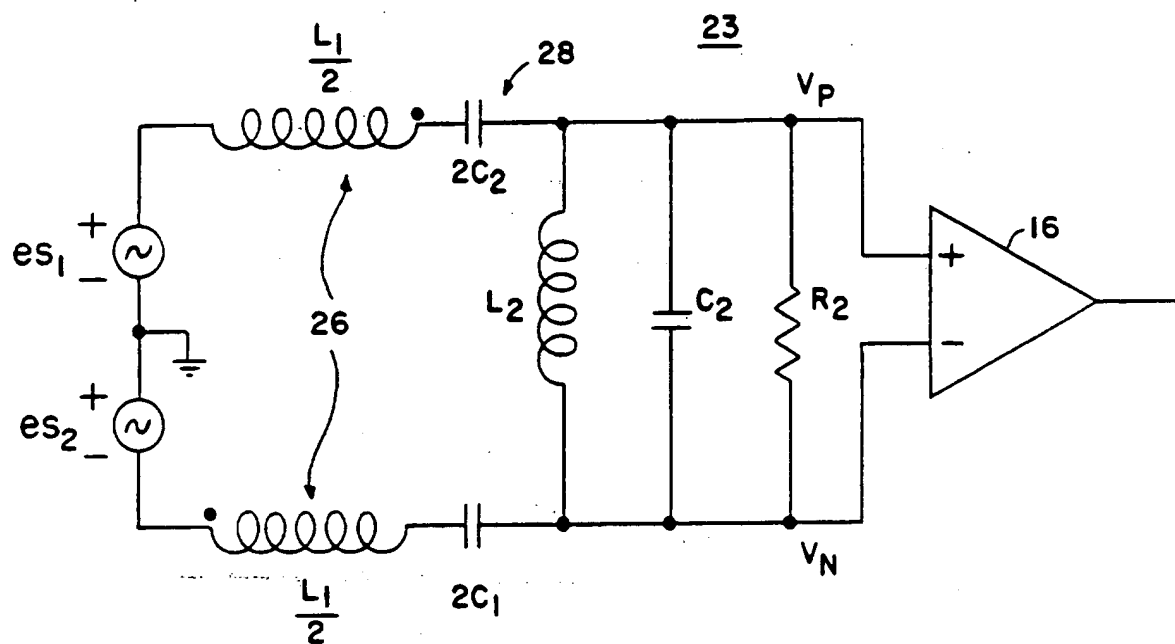
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FIG. 1

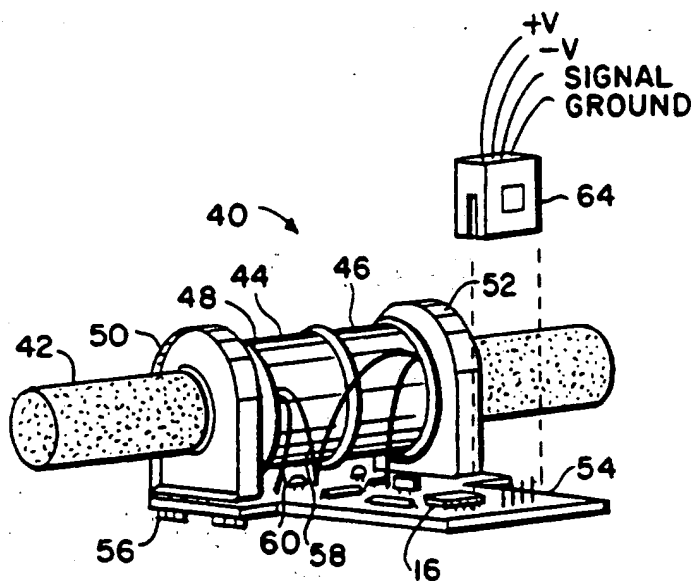FIG.2

FIG.3

FIG.4

FIG.5

FIG.6

BANDPASS FILTERING PREAMPLIFIER

TECHNICAL FIELD OF THE INVENTION

This invention relates to a bandpass filtering preamplifier for a receiver receiving the signal of an underground transmitter used in underground boring equipment.

BACKGROUND OF THE INVENTION

Directional drilling, subsurface boring, micro-tunneling and the like share the objective of producing a hole beneath the surface of the earth in a carefully controlled manner. The hole is usually required for installation of tubular members such as pipes (for natural gas, petroleum fluids, steam, water, other gases and liquids, slurries, or sewer connections), protective conduits (for subsequent installation of electrical wires, cable television lines or fiber optic cable), for direct burial of electric wires and fiber optic cable, and the like. All such activities, particularly those in the top most one hundred feet or 90 of the subsurface, are described as subsurface boring.

Subsurface boring is increasingly important because it allows rapid placement or replacement of gas and water lines, sewers, electrical service, cable television service and similar utility connections with minimal disturbance of roads, landscaping, buildings, and other surface features. Subsurface boring allows placement of pipe and utility connections where conventional surface installation by trenching is impractical or impossible as, for example, when utility connections must cross rivers, canals, major highways, or rail lines. Significant practical and economic advantages are derived from the ability to provide pipe and utility connections with minimal surface disturbance or to provide subsurface crossing of surface barriers.

Locating and communicating with the boring tool are problems that must be solved to realize all advantages of subsurface boring. In many boring tool systems, a small transmitting device called a beacon is installed immediately behind the drill bit. The electromagnetic field generated by

the subsurface beacon is detected at the surface using devices variously called trackers or locators. The beacon's electromagnetic field is often modulated to convey subsurface information from the beacon to the system operator. Beacon

5 signal amplitudes, measured by one or a plurality of surface antennas, can be used to calculate distance between the beacon and the tracker or locator. Depending on beacon modulation details, the subsurface beacon transmits on or around one of several possible frequencies. It is common to allow operation

10 at one of at least two different frequencies, thereby allowing two boring operations to proceed simultaneously in close proximity while still being able to differentiate between the two by using different beacon frequencies.

As operating depth increases, locating and
15 communicating become increasingly difficult because, in the near field, signal amplitude decreases according to the third power of distance. As in any communication system, the signal-to-noise ratio is a primary determinant of success in signal estimation and communication. Beacon power is limited,
20 hence available signal is limited. Accordingly, noise reduction assumes great importance. With limited signal power, the only way to improve the signal-to-noise ratio is to reduce the noise.

The noise figure of the receiving channel in the
25 tracker or locator is determined largely by the preamplifier. Therefore, improvements in the preamplifier relating to signal handling and noise rejection are of great significance to the art.

U.S. Pat. Nos. 5,155,442 and 5,337,002 by Mercer,
30 disclose locator equipment for detecting the magnetic field transmitted by a boring tool of the type that forms a horizontal bore under the surface of the earth. The locator equipment is either hand held, in which case it is maneuvered over the surface to detect the magnetic field transmitted by
35 a small battery-operated transmitter carried by the boring tool, or it is surface mounted at some location determined by the equipment operator. The locator equipment includes a conventional parallel LC resonant circuit to selectively receive the fundamental frequency associated with roll/pitch

information transmitted by the boring tool. The capacitor component of the resonant circuit is apparently variable to either change the resonant frequency of the receiver, or to change the resonant frequency to compensate changes due to
5   aging, temperature, calibration, etc. The shortcomings of such an arrangement are noted below and it is believed that the present invention may overcome them.

SUMMARY OF THE INVENTION

A bandpass preamplifier assembly is disclosed for
10 use with a surface operated receiver having an antenna. For simplicity, all surface operated receivers will be lumped into the generic descriptor "locator". The antenna detects a transmitted signal from either an underground boring device or a signal impressed from a surface transmitter on an
15 underground conductor operating at or around one of several possible characteristic frequencies. The maximum and minimum (or extrema) frequencies of the possible frequency set are the upper and lower cut-off frequencies, respectively. The preamplifier of the preferred embodiment includes a balanced
20 bandpass filter incorporating the antenna as a filter inductance. The filter has a bandpass (or passband) sufficient to pass frequencies between the two spaced-apart frequencies, and attenuates frequencies beyond the upper and lower cut-off frequencies of the filter. A preferred
25 embodiment amplifier is provided with a differential input, and the output of the bandpass filter is connected to the input of the amplifier. When utilizing the filter of the invention in a balanced configuration, the preamplifier assembly provides a high degree of common-mode rejection to
30 extraneous signals induced into the filter circuits.

In accordance with another aspect of the present invention, the balanced bandpass filter is designed in accordance with the Butterworth type. In accordance with another aspect, the bandpass filter is a second order
35 Butterworth filter which provides a high degree of rejection to out-of-band signal and noise frequencies. Yet another advantage of the passive filter of the invention is that of low power, low cost and low noise, which aspects are

especially well adapted for use with battery operated
underground beacon transmitters, and with battery operated
surface locators. Another feature of the invention is that
the antenna, the filter and the amplifier are packaged
5   together as an integral module, and require no digital control
leads which would otherwise carry noise signals that are
characteristic of digital circuits.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present
10   invention and for further advantages thereof, reference is now
made to the following description of the preferred embodiment
taken in conjunction with the accompanying drawings, in which:

FIGURE 1 is an illustrative view of a transmitter
beacon and a locator employing the present invention;

15   FIGURE 2 is a schematic drawing of a normalized
second order Butterworth low pass filter prototype;

FIGURE 3 is a schematic drawing of a single ended
Butterworth prototype bandpass filter;

FIGURE 4 is a schematic drawing of a passive
20   Butterworth bandpass filter in a balanced configuration;

FIGURE 5 is a schematic of a passive balanced
bandpass filter constructed in accordance with the teachings
of the present invention; and

FIGURE 6 is a drawing of the packaged module of the
25   assembly of FIGURE 5.

DETAILED DESCRIPTION OF THE INVENTION

With reference to FIG. 1, there is shown a locator
10 in an environment for locating an underground device, such
as an underground boring tool 12. The locator 10 includes an
30   antenna 14 and a preamplifier 16 for detecting the weak
electromagnetic signals transmitted by a beacon 18 carried by
the boring tool 12 as a bore 20 is formed horizontally under
the surface of the ground 22. The signal received by the
antenna 14 is encumbered with electromagnetic noise, and often
35   the electromagnetic signal is weak because the boring tool 12
can operate fifty feet or more below the surface of the earth.
Moreover, the beacon 18 is often battery operated and thus the

transmitted signal strength is limited to allow sustained periods of underground operation. The earth itself may also attenuate the transmitted electromagnetic energy and thus reduce signal strength as a function of distance. It is well
5   known that signal amplitude decreases according to the third power of distance. It can be seen that signal strength is of paramount importance when the transmitted signal itself is weak to begin with, due to self-contained battery operation of the underground beacon 18 located in the boring tool 12.
10   Underground boring tools and associated beacons are disclosed in U.S. Patent No. 5,133,417, by Rider, and locator equipment and associated receiver circuits are disclosed in U.S. Patent No. 5,264,795, by Rider. The disclosures of both such patents are incorporated herein by reference.

15   In designing a preamplifier assembly for a receiver locator or tracker 10 of the type for receiving the signal rom an underground beacon 18, a number of factors are critical. Noise reduction is a primary objective of the locator analog signal path.   Power consumption and physical volume are
20   concerns of nearly equal importance. As will be discussed hereinafter, the preamplifier assembly constructed in accordance with the teachings of the present invention combines an instrumentation amplifier 16 and the antenna 15 of the locator 10 into a single modular unit, thereby reducing
25   noise pick-up by providing local signal amplification before signals are routed to other electronic functional circuits.

        Antennas for low frequency electromagnetic energy reception, whether of the air or ferrite core type, are modeled as inductors. In conventional practice, the antenna
30   inductance and a capacitor form a parallel resonant circuit having maximum impedance at a frequency determined by the values of the antenna inductance and the resonating capacitance.   Bandwidth about the resonant frequency is determined by the quality factor Q of the parallel circuit.
35   Asymptotic noise rejection away from the resonant frequency is first order with a roll off of about -20 dBV/decade.

        A circuit with high Q has a narrow bandwidth and strongly attenuates signals removed from the resonant frequency.   This is ordinarily desirable, but extreme

selectivity (very high Q) can be disadvantageous. Temperature related component value changes (thermal drift) make the resonant frequency temperature dependent, with the result that a specific beacon frequency and the resonant frequency of the

5 antenna circuit in the locator are neither constant nor optimally matched at all operating temperatures. Multi-frequency operation of such a unit is also difficult. If a beacon operating at one of a pair of possible frequencies is located at the resonant frequency of a parallel resonant

10 circuit, the other beacon frequency is necessarily off-resonance and hence the response is attenuated. Placing the resonant frequency at the geometric mean of the simple mean beacon frequency provides relatively uniform response at both frequencies, but with possibly significant attenuation of both

15 beacon signals. For a simple parallel LC circuit tuned to a mean frequency, signal attenuation increases as the difference between the frequencies increases. It is thus difficult to obtain an acceptable response to a pair of spaced-apart fundamental signals, using a first order parallel LC tuned

20 circuit, without retuning the circuit for each frequency. The Q of a simple resonant circuit is often reduced or spoiled intentionally by adding resistance to the resonant circuit. Reduced circuit Q is known to alleviate the severity of the aforementioned problems, but does not eliminate the problems

25 themselves.

The problem of matching a resonant frequency to a beacon frequency may be overcome by using multiple resonant circuits, switched tuning elements, computer controlled tuning elements, or other similar techniques. A processor-controlled

30 antenna tuning circuit for underground locating equipment is disclosed in U.S. Patent No. 5,231,355, by Rider, et al. The disclosure of such patent is incorporated herein by reference. Such conventional approaches achieve the desired goal of frequency selectivity at the expense of added components,

35 costs, complexity and noise, and with a higher likelihood of component failure.

In one significant application according to the preferred embodiment, the locator 10 is to be used to detect beacon transmitters having at least two distinct extreme

frequencies, namely at or around 29.430 KHz and 32.768 KHz. A simple parallel resonant circuit approach is not optimal for a locator to detect and process signals from beacons at either of these two frequencies which are spaced apart about 3.3 KHz. The geometric mean of the two beacon frequencies is 31.054 KHz. An ideal bandpass filter with a center frequency of 31.054 KHz and a bandwidth of approximately 3.5 KHz would pass both beacon frequencies, and any frequency therebetween, without attenuation and provide infinite out-of-band noise rejection. Although a mathematically ideal bandpass filter is unrealizable in practical circuits, a physically realizable narrow bandpass filter structure will provide excellent selectivity without elaborate tuning or switching schemes. A bandpass filter can present almost arbitrarily steep rejection to out-of-band signals by increasing the order of the lowpass filter prototype on which it is based. It is also appreciated that, as the order of the filter is increased to provide increased selectivity and reduced response to frequencies outside the band, the circuit complexity and cost increase correspondingly.

A key element of the locator 10 is the antenna 14. One typical antenna 14 used in the type of locator 10 of interest is a dual-winding bobbin formed around a ferrite rod or core. In a typical antenna of this type, the antenna has a total inductance of approximately one Henry (H) at 31.054 KHz when the bobbin windings are series connected. The actual inductance is variable from antenna to antenna, being strongly dependent on the individual ferrite rod, the unique fabrication details of the individual bobbin windings, and the resulting antenna behavior due to self-resonant effects. For purposes of discussing a design hereinafter, an example of an antenna with total series inductance of 1.118 H composed of two equal and independent bobbin windings is assumed. In reality, it is difficult to characterize the inductance of a multiple winding antenna bobbin. A precise description must take into account distinctions to be made between the self-inductances of each bobbin winding and the mutual inductances shared by the bobbin windings. This is a non-trivial problem, compounded in difficulty by frequency

dependent effects near self-resonance. Typical antennas having an inductance of 1.118 H at 31.054 KHz are self-resonant at approximately 38 KHz, which severely handicaps the design process. In addition, antenna inductance is often not 5 even locally constant in the bandpass frequency range. However, the design process described hereinafter yields results useful as a first approximation to an end design.

Passive inductance-capacitance (LC) filters are commonly designed using data tabulated in reference materials. 10 LC filter prototypes are commonly found in two forms: a capacitive input (probably the more commonly used) and an inductive input dual. Because the signal source for the preamplifier 16 is the inductive antenna element 14, the inductive dual form is employed. Furthermore, passive LC 15 filter prototypes require known relationships between source and load impedances. In the preamplifier assembly 23 of the invention shown in FIG. 5, the antenna inductance 26 is part of filter 28 connected to the input of an instrumentation amplifier 16. The relatively low impedance of the antenna 14 20 produces induced signals which are filtered and connected to the very high impedance input of the instrumentation amplifier 16. Impedance mismatches greater than 20:1 are usually considered infinite, resulting in a normalized circuit model having zero source impedance and unit load impedance.

25 Filter order and type (Butterworth, Bessel, Chevyshev, etc.) are matters of design choice. The preferred embodiment preamplifier assembly 23 is based on a Butterworth prototype to provide reasonable stop band roll-off with a maximally smooth passband. The uniformity of response at the 30 various beacon frequencies is important. This fact makes the ripples inherent in Chevyshev, elliptic (Cauer), and certain other filter prototypes undesirable. FIGURE 2 is schematic of the basic Butterworth second order (N=2) lowpass filter prototype with normalized component values, including a series 35 resistance R_1 (approximately zero ohms in the normalized model) and series inductance L_1, a shunt capacitance C_2 and shunt resistance R_2. Voltage is applied to the circuit by a voltage generator 30 generating a voltage V_{IN}. The output of

the circuit is taken across the resistor R_2 and is identified as V_{OUT}.

Based on the desired bandpass described above, one can assume operation of a bandpass filter with a 6 KHz
5   bandpass. This requires the lowpass filter prototype be frequency scaled to provide this 6 KHz bandwidth. The frequency scale factor (FSF) is given by the equation:

$$FSF = 2\pi(6000 \text{ Hz}) = 37.70 \times 10^3 \text{ rad/sec}$$

Reactive elements are divided by the FSF, whereas
10   resistive elements (being independent of frequency) are not frequency scaled. The frequency scaled second order Butterworth circuit results in an inductance L_1 of 30.27 mH, a capacitance C_2 of 18.76 μF and a resistance R_2 of one Ω. R_1 is negligible and assumed to be essentially zero Ω.

15   Impedance scaling is carried out to achieve component values of practical sizes. As mentioned above, an actual antenna impedance is assumed to be approximately 1.118 H at 31.054 KHz. The frequency scaled inductance noted above is about 30.27 mH. Since antenna inductance is difficult to
20   manipulate, it is normally necessary to impedance normalize other components to reconcile the inductances of the scaled filter and the antenna inductance. Hence, the impedance scaling factor Z is given by the equation:

$$Z = (1.118 \text{ H})/(30.27 \text{ mH}) = 36.93 \times 10^3$$

25   All elements thus require impedance scaling with respect to the antenna impedance. Inductors and resistors are multiplied by Z, whereas capacitors are divided by Z. The frequency and impedance scaled second order Butterworth lowpass circuit results in an inductance L1 of the necessary
30   1.118 H, a capacitance C_2 of 508 pF and a resistance R_2 of 36.93 KΩ.

Transforming the lowpass prototype filter to a bandpass structure is accomplished by series resonating series branch reactances and parallel resonating shunt branch reactances at
35   the geometric mean frequency of 31.054 KHz to form the second order bandpass filter 32 illustrated in FIGURE 3. Filter 32 is a single ended filter, i.e., unbalanced with respect to the signal ground. The filter 32 includes series inductance L_1 and series capacitance C_1, shunt inductance L_2, shunt

capacitance C_2, and shunt resistance R_2. Based on a geometric mean frequency of 31.054 RHz, L_1 is 1.118 H, C_1 is 23.49 pF, L_2 is 51.71 mH, C_2 is 508 pF and R_2 is 36.93 KΩ.

5   A passive filter configuration balanced with respect to circuit ground is obtained by recognizing that the circuit transfer function is preserved by dividing the series branch inductance L_1 by two and multiplying series branch capacitance C_1 by two, as illustrated in the second order Butterworth balanced bandpass filter 34 illustrated in FIGURE 4. The

10   balanced passive filter has a bandpass sufficient to accommodate a number of frequencies within the 6-7 KHz passband, without using multiple tuned circuits for a respective multiple number of frequencies, without using switched tuning elements, processor-controlled tuning or other

15   more complicated active filter circuits. The second order passive filter according to the invention provides a -40 dBV/decade asymptotic rolloff, as compared to a -20 dBV/decade rolloff of a simple parallel resonant circuit, such as described in the Mercer patents identified above. The result

20   is a balanced second order Butterworth bandpass filter which is optimal for rejection of common-mode noise by instrumentation amplifier 16. The phasing of the resulting inductance L_1 is shown by the dot convention, i.e., as series aiding.

25   The completed preamplifier assembly 23 of the present invention is illustrated in FIGURE 5. It is often useful to obtain an analytic transfer function in the Laplace transform domain using the Laplace transform variable s-i2πf. To make the required algebra manageable, two assumptions are

30   important. The first assumption is that the total series-connected antenna inductance L_1 is equally divided between the two bobbin windings. The second assumption is that the two bobbin windings can be modeled by a simple independent inductors. Self-resonant effects and winding resistance can

35   be accommodated, at least in a local sense, by more complicated models. Given the difficulty of determining actual interrelationships between bobbin windings, a more complex model does not contribute a great deal of practical insight.

The instrumentation amplifier 16 input impedance is assumed to be resistive and significantly higher than the filter output impedance. Signal voltages e_{s1} and e_{s2} are induced in the windings of the antenna inductance L_1 by the

5 electromagnetic field produced by the beacon signal. Although the beacon transmitter 18 may not transmit the plural frequencies simultaneously, such a transmitter is nevertheless adapted for transmitting plural frequencies. Surface-mounted locating transmitters are adapted for transmitting a number

10 of different frequencies simultaneously. Under the assumption of using two equal and independent bobbin windings, antenna inductances in the balanced configuration are moth one-half L_1. The bobbin windings are assumed to have not significant resistive losses, a condition reasonable approximated in

15 practice. Similarly, the total antenna inductance L_1 is resonated by a series capacitance C_1 in the unbalanced model at about a midpoint frequency. The parallel resonant L_2C_2 circuit is resonant at about the same frequency that lies at the geometric mean between the extrema frequencies that are

20 passed by the filter 34. The two series L_1C_1 circuits present a low impedance at the geometric mean frequency, while the parallel L_2C_2 circuit presents a high impedance at the geometric mean frequency. This balanced filter arrangement therefore provides a bandpass filter to pass the extrema

25 frequencies and all the frequencies therebetween.

When the equivalent models are transferred to a balanced configuration, the capacitances required in the two series branches become $2C_1$. The transfer function relating the differential voltage $V_P - V_N$ across R_2, L_2 and C_2 resulting

30 from the induced signal voltages e_{s1} and e_{s2} in the bobbin windings, is defined in accordance with the following:

$$\frac{V_P - V_N}{e_{s1} + e_{s2}} = \frac{s^2 R_2 L_2 C_1}{s^4 R_2 L_1 C_1 L_2 C_2 + s^3 L_2 C_1 L_2 + s^2 (R_2 L_1 C_1 + R_2 L_2 C_1 + R_2 L_2 C_2) + s^1 L_2 + R_2}$$

Knowledge of the transfer function is useful for modeling circuit behavior once component values are known.

It is very useful to understand the relationships

35 between circuit elements of the general circuit model of FIGURE 5, tabulated element values of the lowpass prototype

of FIGURE 2 and critical frequency-domain descriptors. While the design procedure usually follows the nearly graphical steps used above, the individual transformations may be condensed to obtain the algebraic relationships which follow.
5 The resulting values are good first approximations to practical design values.

Definition of Variables:

f_{GM} geometric mean frequency of bandpass filter.

f_{BW} -3 dBV bandwidth of bandpass section, also the -3
10   dBV bandwidth of the lowpass prototype.

FSF   frequency scaling factor: $FSF=2\pi f_{BW}$

L_{TAB} tabulated inductance from Butterworth lowpass prototype.

L_1 measured inductance of series-connected antenna
15   coil.

L_2 shunt branch inductance of balanced bandpass filter.

C_{TAB} tabulated capacitance from Butterworth lowpass prototype.

C_1 capacitance required to resonate series-connected
20   antenna inductance L_1.

C_2 shunt branch capacitance of balanced bandpass filter.

R_2 shunt branch resistance of balanced bandpass filter.

Z impedance scaling factor.

25   Impedance scaling factor Z is determined from the antenna inductance under the assumption that antenna inductance will be changed only under redesign or the like.

$$Z=\left(\frac{L_1}{L_{TAB}}\right)FSF,$$

where

$$FSF=2\pi F_{BW}$$

Knowing Z and FSF, circuit elements as shown in Figure 4 are given by

$$L_1 = \frac{L_{TAB} \cdot Z}{FSF}$$

$$C_1 = \left[\frac{1}{2\pi f_{CM} \sqrt{L_1}} \right]^2$$

$$R_2 = Z$$

$$C_2 = \frac{C_{TAB}}{FSF \cdot Z}$$

$$L_2 = \left[\frac{1}{2\pi f_{CM} \sqrt{C_2}} \right]^2$$

The preamplifier assembly 23 is preferably powered by batteries. This eliminates power supply noise, particularly high frequency switch mode power supply noise. For example, one circuit constructed in accordance with the teachings of the present invention employs two nine-volt alkaline batteries with a current drain of less than 0.3 mA from each of the batteries, resulting in a total nominal power consumption of only 5.4 mW. This arrangement, having a bandwidth between 6.5 KHz and 7 KHz, presents minimal attenuation to 29.430 and 32.768 KHz beacon frequencies, allows for some degree of passband thermal drift, and provides second order rejection of noise outside the passband. Primary causes of thermal drift are believed to be the temperature coefficient of the antenna ferrite rod and exaggerated changes in antenna inductance due to operation near antenna self resonance. These problems may be reduced by using woven-wire Litz wire antenna bobbins (rather than the 34 AWG copper wire

presently utilized as the antenna coil windings) which nearly doubles the self-resonant frequency, by using air core antennas to eliminate the ferrite rod all together and by using special winding techniques.

The preamplifier assembly 23 can be utilized to provide high gain (40 dBV or x 100 gain) with the noise reduction of a second or higher order bandpass amplifier. While a second order bandpass amplifier is disclosed herein, the filter order is a matter of choice. Higher order filters can be used to additionally improve rejection of out-of-band noise. Antenna inductance is incorporated in the filter as a circuit element making all circuit values dependent on the antenna. In one filter constructed in accordance with the teachings of the present invention $C_1 = 47$ pF, $L_2 = 47$ mH, $C_2=560$ pF and $R_2=30.1$ KΩ. An instrumentation amplifier suitable for use with the passive balanced filter can be a 1NA118CP unit. This instrumentation amplifier provides a gain of about 100 (+40 dBV), and when coupled to a balanced bandpass filter described above, it attenuates any common-mode signals that are externally induced into the preamplifier assembly 23. The bandpass preamplifier assembly 23 of the present invention is well adapted for mass assembly and production without using high tolerance components. This advantage results in a lower cost unit that is reliable and provides excellent performance.

The method of design of an appropriate filter as described above is also presented in the book _Electronic Filter Design Handbook_, authored by Arthur B. Williams, copyright 1981, published by McGraw-Hill Book Company, ISBN 0-07-070430-9, the text of which is incorporated by reference herein in its entirety.

With reference to FIG. 6, there is illustrated the packaged module 40 comprising the bandpass preamplifier assembly according to the preferred embodiment of the invention. The preamplifier module 40 includes a ferrite core 42 around which are wrapped a first antenna coil 44 and a second antenna coil 46. The antenna coil windings 44 and 46 are each wrapped around a plastic bobbin 48 having outside radial dividers, as well as a central radial divider for

providing a pair of annular channels in which the conductors of the windings 44 and 46 can be wound. The bobbin 48 has a central bore therethrough to allow the ferrite rod 42 to extend therethrough. The coil windings 44 and 46, together

5 with the ferrite core 42 function as an antenna to receive the electromagnetic energy transmitted by the beacon transmitter 18 of the underground boring tool 12. The ferrite rod 42 is attached at each end thereof to a vertical support 50 and 52, which supports provide a stand-off of the antenna structure

10 from a printed circuit board 54. Indeed, the supports 50 and 52 are fastened to the printed circuit board 54 by way of plastic fasteners, such as shown by reference character 56. A pair of coil winding conductors 58 are connected together and to a circuit common connection of the printed circuit

15 board 54. The other conductors 60 and 62 of the respective coil windings 40 and 46, are connected to series capacitors soldered to the printed circuit board 54, to form the pair of series resonant circuits. The other components of the filter 34 shown in FIG. 4, are also soldered to the printed circuit

20 board 54. The instrumentation amplifier 16 is also mounted on the printed circuit board 54, with differential inputs connected to the balanced filter. A signal output of the instrumentation amplifier 16 as well as positive and negative supply voltage terminals, and a ground terminal, are the only

25 conductors coupled to the module 40. The four conductors are connected to female sockets (not shown) formed in a plastic connector 64 which, in turn, connects to a corresponding connector with contact pins (not shown), which are connected to the printed circuit board 54. In this manner, no digital

30 signal leads are connected to the bandpass preamplifier assembly to thereby provide a source of noise to the preamplifier circuits. It can be appreciated that low level noise signals common to digital signal leads can adversely affect preamplifier circuits which have high gain factors and

35 are designed for amplifying low level signals.

The preamplifier module 40 is packaged as a unitary module for easy mounting within a non-conductive case of a hand-held locator 10. Further, the bandpass nature of the assembly is well adapted for receiving plural frequencies of

electromagnetic signals transmitted by underground beacon transmitters.

As noted above, a capacitive input filter can be easily designed by employing the dual analysis of the inductive input filter. Those skilled in the art, together with the textbook noted above, can configure a capacitive input filter for use with a capacitor plate type antennas to receive a band of electric field frequencies, rather than electromagnetic fields. For the same reasons that a capacitor is the dual of an inductor, and vice versa, an electric E-field is the dual of a magnetic H-field. Under a reasoning similar to the foregoing, but using the dual analysis, the capacitor of an antenna can be the electrical component as the input to the filter. This filter configuration is well adapted for sensing electric field frequencies within a band, such as for detecting electric fields emitting from underground boring tool transmitters.

The foregoing is directed to a preferred embodiment of the invention as utilized in conjunction with receivers for detecting the location of underground conductors, when amplitude modulated signals are radiated from the underground conductors and detected by surface locator receivers. It is to be understood that the invention can be utilized with no modulation at all, or with other modulation techniques such as frequency modulation, phase modulation, etc. The filter of the invention may also be employed with antennas having an air core, or a core material other than ferrite, and with one or more than two coil windings of the antenna.

Although the present invention has been described with respect to a specific preferred embodiment thereof, various changes and modifications may be suggested to one skilled in the art, and it is intended that the present invention encompass such changes and modifications as fall within the scope of the appended claims.

CLAIMS

1. A bandpass preamplifier for a receiver having an antenna for detecting signals transmitted from an underground conductor operating at a plurality of
5 frequencies with extrema characterized by a first characteristic frequency and a second characteristic frequency, comprising:

a bandpass filter including the antenna defining an electrical component of the filter, said filter
10 having a bandpass including the first and second characteristic frequencies, and an output; and

an amplifier having an input, the output of the bandpass filter connected to the input of the amplifier.

2. The bandpass preamplifier assembly of Claim
15 1, wherein said bandpass is an inductive input filter with the electrical component of the antenna defining at least one inductor.

3. The bandpass preamplifier assembly of Claim 1, wherein the bandpass filter is of a Butterworth design.

20 4. The bandpass preamplifier assembly of Claim 1, wherein the bandpass filter is a second order filter.

5. The bandpass preamplifier assembly of Claim 1, wherein the first characteristic frequency is less than 29.430 KHz and the second characteristic frequency is greater
25 than 32.768 KHz.

6. The bandpass preamplifier assembly of Claim 1, wherein the bandpass filter is designed in accordance with the following, where

f_{GM} geometric mean frequency of bandpass filter.

30 f_{BW} -3 dBV bandwidth of bandpass section, also the -3 dBV bandwidth of the lowpass prototype.

FSF	frequency scaling factor: $FSF=2\pi f_{BW}$
L_{TAB}	tabulated inductance from Butterworth lowpass prototype.
L_1	measured inductance of series-connected antenna coil.
L_2	shunt branch inductance of balanced bandpass filter.
C_{TAB}	tabulated capacitance from Butterworth lowpass prototype.
C_1	capacitance required to resonate series-connected antenna inductance L_1.
C_2	shunt branch capacitance of balanced bandpass filter.
R_2	shunt branch resistance of balanced bandpass filter.
Z	impedance scaling factor, and

$$Z=\left(\frac{L_1}{L_{TAB}}\right)FSF,$$

$$FSF=2\pi f_{BW}$$

$$L_1=\frac{L_{TAB}\cdot Z}{FSF}$$

$$C_1=\left[\frac{1}{2\pi f_{GM}\sqrt{L_1}}\right]^2$$

$$R_2=Z$$

$$C_2=\frac{C_{TAB}}{FSF\cdot Z}$$

$$L_2 = \left[\frac{1}{2\pi f_{GM} \sqrt{C_2}} \right]^2 .$$

7. The bandpass preamplifier assembly of Claim 1, wherein the antenna comprises a ferrite core with a pair of windings wound therearound.

8. The bandpass preamplifier assembly of Claim 7,
5   wherein the pair of windings are connected in series.

9. The bandpass preamplifier assembly of Claim 1, wherein the amplifier comprises a differential amplifier with inputs connected to the balanced filter.

10. The bandpass preamplifier assembly of Claim 1,
10   wherein said filter is passive and balanced so that the output thereof provides differential signals to a differential input of the amplifier.

11. A bandpass preamplifier for a receiver having an antenna for detecting signals transmitted from an
15   underground conductor operating at a plurality of frequencies with extrema characterized by a first characteristic frequency and a second characteristic frequency, comprising:
    a balanced bandpass filter including,
        an antenna inductance defined by a pair of
20   series-connected coil windings, said coil windings having induced therein electromagnetic signals transmitted by the underground transmitter, a pair of capacitors, each connected in series with a respective said coil winding, a parallel inductor-
25   capacitor resonant circuit connected between output terminals of said pair of capacitors; and

a differential amplifier connected to the output terminals.

12. The bandpass preamplifier of Claim 11, wherein said coil winding and said pair of capacitors define a
5   pair of series resonant circuits, and said shunt LC circuit comprises a parallel resonant circuit.

13. The bandpass preamplifier assembly of Claim 12, wherein each said series resonant circuit resonates at a frequency substantially midway between the extrema
10   frequencies.

14. The bandpass preamplifier assembly of Claim 13, wherein the parallel resonant LC circuit resonates at a frequency substantially midway between the extrema frequencies.

15   15. The bandpass preamplifier assembly of Claim 11, further including a resistor in parallel with the parallel LC circuit to achieve a desired Q to the parallel resonant circuit.

16. The bandpass preamplifier assembly of Claim 11,
20   wherein the inductance of each said coil winding is substantially the same value, and the pair of capacitors are of substantially the same value.

17. The bandpass preamplifier assembly of Claim 11, wherein a junction connection between the two coil windings
25   is connected to a circuit common voltage.

18. The bandpass preamplifier of Claim 11, wherein said filter, said antenna and said amplifier are packaged together as an integral module.

19. A method fabricating a bandpass preamplifier for
30   a receiver having an antenna for detecting signals

transmitted from an underground conductor operating at a plurality of frequencies bounded by a first characteristic frequency and a second characteristic frequency, the method comprising the steps of:

5   constructing a passive passband filter using a pair of antenna inductors in series with a respective capacitor to form two series tuned circuits, with the series capacitors defining a differential output of the filter;

10   constructing a parallel LC tuned circuit and bridging the parallel tuned circuit across the filter output;

            connecting the differential output of the filter to a differential input of a differential

15   amplifier; and

            packaging the antenna, the filter and the amplifier as a single unit for use in the receiver.

20. The method of Claim 19, further including selecting passive components of the filter to achieve at

20   least about a 6.5 RHz bandwidth at frequencies in the range of about 28 KHz to about 33 KHz.

21. The method of Claim 19, further including connecting the antenna inductors directly together in series aiding.

25   22. The method of Claim 19, further including providing only power, ground and signal wires to the package, without any digital control wires.

23. The method of Claim 19, further including operating the receiver with a DC battery to power the

30   amplifier, and operating the receiver to detect electromagnetic signals transmitted from an underground boring device having a beacon transmitter adapted to transmit plural frequencies within the bandwidth of the filter of the receiver.

24. A bandpass preamplifier assembly having a balanced bandpass filter with second order filtration characteristics; and an antenna forming the series inductance in the filter, the assembly providing reception of distinct
5   beacon frequencies.

25. A bandpass preamplifier substantially as hereinbefore described with reference to and as illustrated in Figs. 5 and 6 of the accompanying drawings.

26. A method of fabricating a bandpass preamplifier substantially as hereinbefore described with reference to and as illustrated in Figs. 5 and 6 of the accompanying drawings.

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Claims searched: 1 to 26

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Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.O): G1N NDUP; H3U UQF; H3W WVT

Int Cl (Ed.6): E21B; H03H; G01V

Other: Online: WPI

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
		1 at least
X	GB2060304A (FUJITSU TEN)	

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
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